

LARGE AREA, LOW FLUENCE ELECTRON BEAM GENERATION ON CASINO

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ABSTRACT

A large area (approximately 730 cm²), low fluence (~1 kA/cm²) electron beam has been produced on the Casino simulator. The beam is extracted from a 10 cm diameter cathode, through a 1 mil thick titanium anode foil, and transported to a target volume approximately one meter downstream. The beam is immersed in a dc magnetic field of up to 4 T in the diode region, decreasing to 0.4 T in the target chamber. Beam currents ranging from 250 kA to 900 kA have been measured in the diode, with diode voltages from 500 kV to 1.1 MV, depending on the anode-cathode gap spacing.

INTRODUCTION

The goal of the present work is to implement a low current density, large volume electron beam capability for the simulation of a high-fluence soft x-ray environment on the Casino simulator. Casino has previously delivered a 60 ns, 550 kA electron beam with a mean electron energy of 800 keV, and endpoint energy of 1.2 MeV, to a 25 cm² target area using pulsed magnetic field coils. The low current density electron beam will be used to simulate a cold x-ray environment for three-dimensional cryogenically cooled objects, such as: mirrors, IR detectors, structural support members, etc., with cross-sectional areas up to 730 cm².

The Casino electron beam transport system is shown schematically in Figure 1. The electron beam is generated from a 10 cm (4 inch) diameter contoured field emission cathode immersed in a 3 T magnetic field. Three independent superconducting dc magnets guide the beam approximately 1 meter downstream to the target area and permit variation in the beam expansion. The superconducting coils allow dc operation of the magnetic field, eliminating eddy current heating effects and impulse forces on cold test objects in the target area. At the nominal design field ratio of 10:1 from the cathode to the target, the electron beam area expands by a factor of 9, from 4 inches in diameter at the cathode to 30.5 cm in diameter approximately 1 meter downstream at the target. The electron beam is transported to the target with 1-3 Torr of helium in the propagation cell. The effective endpoint and average electron energies are adjustable by inserting various thickness scattering foils in the electron beam path.

DESIGN OF THE BEAM GENERATION AND TRANSPORT SYSTEM

Particle-in-Cell (PIC) simulations were performed to assist in the design of the diode and transport region by modeling the electron beam generation and transport using the 2-D MAGIC code¹. Initial simulations of the diode indicated that a very uniform current density beam could be obtained from a conically recessed (dish) cathode - planar anode geometry. The 10 cm diameter cathode had a 1.75° inward taper to the beam axis as measured from the anode plane. The minimum anode-cathode gap spacing was 5.4 mm. For a diode voltage of 1.2 MV, the diode current in the simulation was seen to be about 500 kA. A minimum axial magnetic field of 2 T is required in the diode to keep the beam from pinching on axis.

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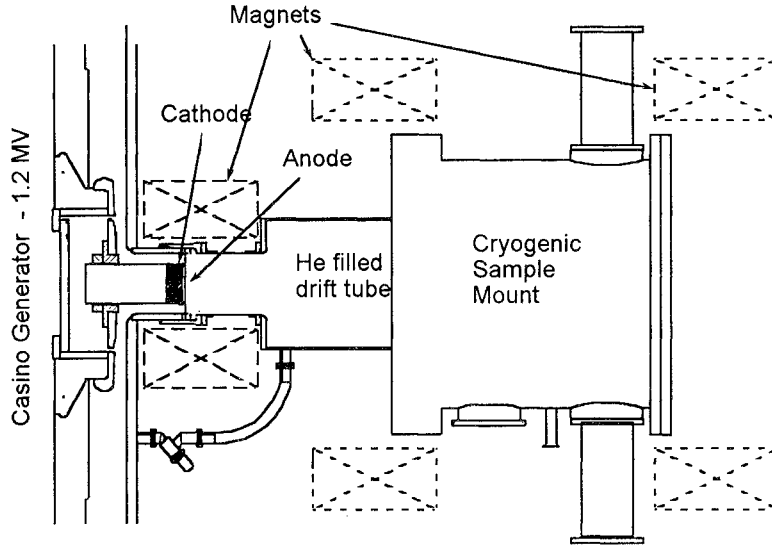


Figure 1. Schematic of the Casino electron beam transport system.

The PIC code was also used to determine the minimum value of magnetic field required to maintain beam uniformity in the test region. The factors which determined the lower bound on this magnetic field were: (i) avoidance of beam filamentation, and (ii) the need to minimize the effect of induced currents flowing in the test object. These currents set up fields which can distort the beam causing nonuniform exposure of the sample. Beam filamentation can be suppressed if the minimum axial magnetic field along the transport region exceeds the following threshold:²

$$B_z(z)^{\min} \geq 47\beta_z[\gamma J(z)]^{1/2} \quad (1)$$

where $B_z(z)$ is in kG, $\beta_z = v_z / c$ is the relativistic axial component of the beam velocity, $\gamma = 1 + eV / mc^2$ is the usual relativistic factor, and $J(z)$ is the beam current density in A/cm². For nominal beam parameters of 500 kA, and 1 MeV, the minimum field at the diode (high field region) is about 4.2 kG, and the minimum field in the test volume (low-field region) is about 0.8 kG. The PIC code results show the energy density of the electron beam to be 2 - 10 cal/cm² over the 730 cm² simulation area, and uniform to within 10% at the target.

The axial magnetic field produced by the three independent superconducting coils peaks about 6 cm downstream from the anode, which causes the beam to compress slightly before expanding in the reduced field region. For a space-charge and current neutralized beam immersed in a magnetic field, the electrons follow the magnetic field lines and a simple expression for the beam radius can be written:

$$r(z) = r_o \sqrt{\frac{B_o}{B_z(z)}} \quad (2)$$

where $r(z)$ is the radius of the beam at a location where the magnetic field is given by $B_z(z)$, and r_o is a known beam radius at a reference field B_o . Figure 2 shows the electron beam envelope calculated from Eq. (2) superimposed over the locations of the wall of the transport chamber. Also shown is the profile of the axial magnetic field and experimental beam size data as measured in the test area with radiachromic dye film. The agreement between the experimentally measured beam size and the simple model is quite good and confirms the utility of this simple model as a design tool.

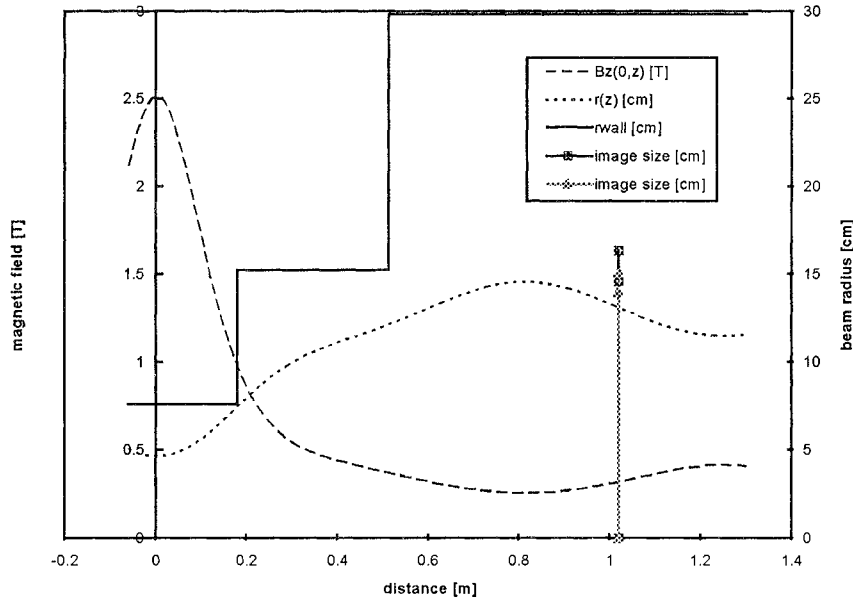


Figure 2. Magnetic field profile and comparison with simple charged neutralized beam model in which the electrons follow the magnetic field lines.

EXPERIMENTAL RESULTS AND BEAM UNIFORMITY MEASUREMENTS

The electron beam current is measured in the diode region using a pair of segmented Rogowski coils as well as a pair of resistive current (button) shunts. Current measurements in the transport region are not feasible due to the almost complete current neutralization in the 2 - 3 Torr helium. The voltage is measured using a capacitive probe in the water filled transmission line. An inductance $(-L di/dt)$ correction is made to this signal, using the inductance determined from a short-circuit shot, to estimate the voltage across the diode. The inductance determined from the short-circuit shots was about 60 nH, resulting in a substantial drop in the voltage actually applied across the anode-cathode gap. Two types of cathode materials have been investigated: graphite and velvet covered stainless steel. The velvet cathodes were investigated to see if they could provide improved cathode surface emission uniformity. The anode consists of a 1 mil thick Ti foil, and separates the helium filled transport chamber from the vacuum diode. Before entering the large diameter (61 cm) test chamber, the beam passes through a stainless steel scattering foil to decrease the electron endpoint energy to the desired level, and increase the angular divergence of the beam to improve the uniformity on target. The scattering foil thickness has been varied over a range of 2.2 to 6.6 mils. Electron beam uniformity was measured in the target region using radiachromic dye film directly exposed to the electron beam. The resulting exposed films are scanned with a Joyce-Loebl microdensitometer to determine uniformity.

Figure 3 presents experimental data from shot 998 obtained using a planar velvet cathode (0° recess angle) with a diode gap separation of 7 mm. From a peak voltage signal of 1.1 MV measured in the water, the calculated diode voltage is reduced to 625 kV. The peak current is 700 kA measured with the segmented Rogowski coils, although differences as great as 25% have been observed between the Rogowski coils and the resistive current shunts. In general, the observed currents are higher than expected, although there seems to be a wide variation in pulsewidth and amplitude. The space charge limited (Child-Langmuir) electron emission current in a planar diode, for diode voltages in the range $0.5 \text{ MV} < V < 10 \text{ MV}$, can be written as a function of time, t in the form:³

$$J \approx \frac{2.72 \times 10^3}{(d - ut)^2} [\gamma^{1/2} - 0.8471]^2 \quad [\text{A/cm}^2] \quad (3)$$

where d is the diode gap in cm, and u is the diode plasma closure velocity. Plasma closure velocities can range up to $6 \text{ cm}/\mu\text{s}$. From the data of shot 998, assuming no plasma closure in the diode, the peak space charge limited electron emission current should be about 186 kA. The measured current in the diode of 700 kA suggests that diode closure is significantly influencing the emission later in the pulse. The FWHM of the power pulse is calculated from the measured current and voltage signals to be 73 ns for this shot. The total energy delivered by the diode is 26 kJ.

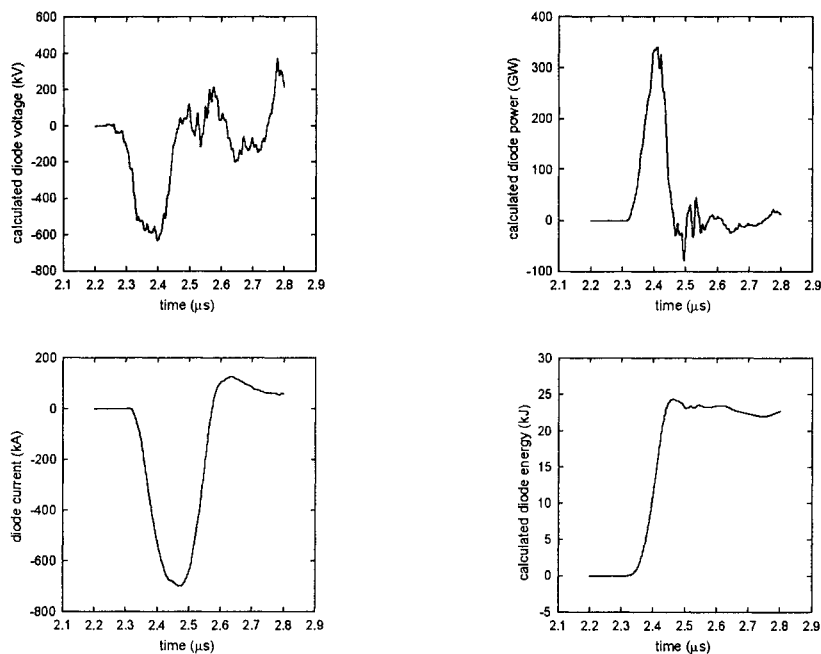


Figure 3. Calculated diode voltage, diode current, calculated diode power, and calculated diode energy from shot 998.

The time integrated electron spectrum is calculated from the diode current and calculated diode voltage waveforms by integrating the current obtained for a particular voltage step. The spectrum obtained from the data of shot 998 is shown in Figure 4.

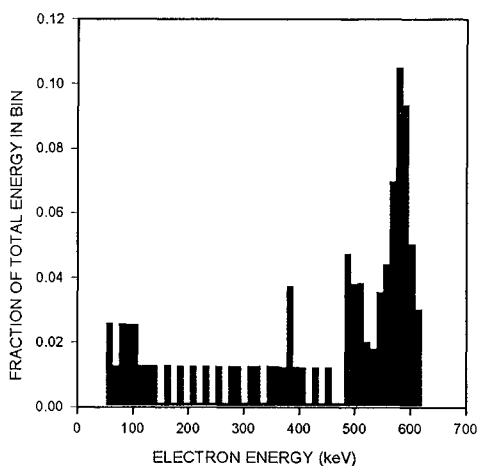


Figure 4. Electron beam spectrum from Casino e-beam shot 998.

Behavior of the two different cathode materials was not significantly different. Graphite cathodes appeared to give slightly improved uniformity as measured at the target with the radiachromic film, however the velvet cathodes generated significantly less debris. Diode closure appears to be a problem irrespective of which type of cathode material is used. Figure 5 shows the beam profile obtained on shot 975 from scanning the exposed radiachromic film with a microdensitometer. Direct examination of the film indicates some structure in the form of flutes around the circumference of the image, but the uniformity is quite good ($\pm 15\%$) across the body of the 30 cm diameter beam.

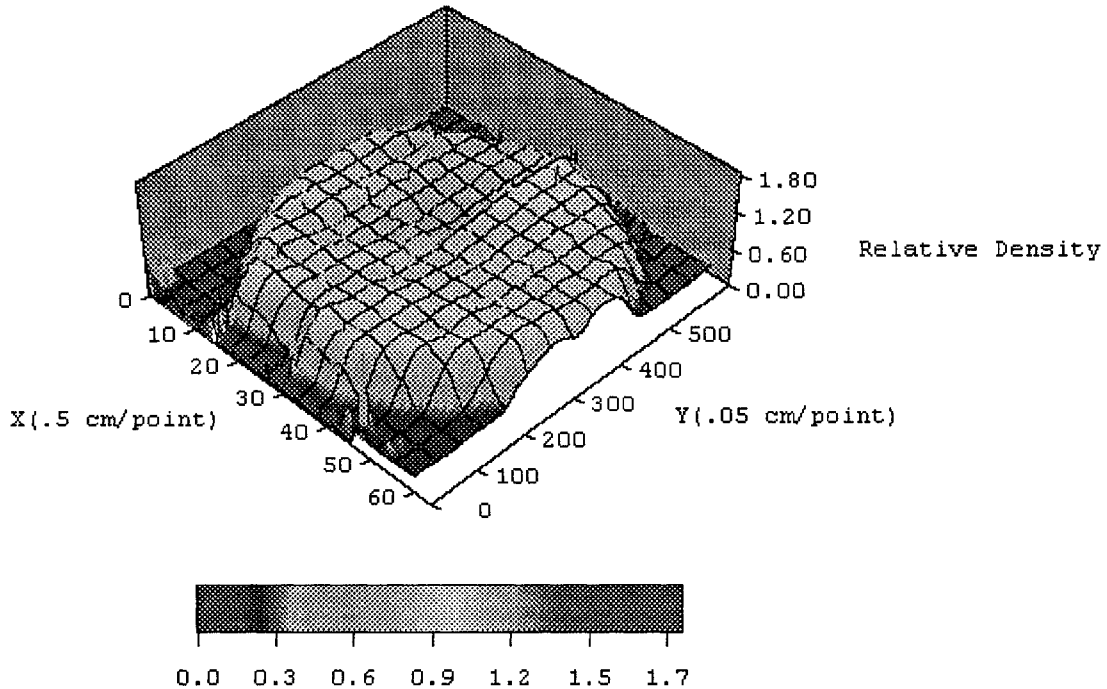


Figure 5. Electron beam uniformity measured from scanned radiachromic dye film.

Efforts to reduce the electron beam current and increase the effective electron endpoint energy by increasing the diode gap spacing have proved generally inconclusive. Increasing the gap spacing from 5.4 to 7.8 mm seems to improve the uniformity, but the effect on the observed diode current is not as pronounced as expected. Improved uniformity was generally obtained by increasing the thickness of the stainless steel scattering foil from 2.2 mils (56 μm) to 6.6 mils (168 μm). Insufficient shots have been taken under constant diode conditions to really quantify the reproducibility. Energy deposition measurements will be made in the near future using a large diameter (33 cm) calorimeter array consisting of total stopping calorimeters, thin foil calorimeter stacks for depth dose measurement and thermoelastic depth dose calorimeters.

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